Life Cycle Assessment of Bio-based and Fossil-based plastic: A Review

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Abstract

This review assesses the state-of-the-art in comparative Life Cycle Assessment of fossil-based and bio-based polymers. Published assessments are critically reviewed and compared to the European Union Product Environmental Footprint (EU PEF) standards. No published articles were found to fully meet the standards, but the critical review method was used to classify the articles by their level of compliance. 25 articles partially met the PEF standards, giving 39 fossil-based and 50 bio-based polymer case results. Ultimately, it was possible to compare seven bio-based polymers and seven fossil-based polymers across seven impact categories (energy use, ecotoxicity, acidification, eutrophication, climate change, particulate matter formation and ozone depletion). Significant variation was found between polymer types and between fossil-based and bio-based polymers, meaning it was not possible to conclusively declare any polymer type as having the least environmental impact in any category. Significant variation was also seen between different studies of the same polymer, for both fossil-based and bio-based polymers. In some cases this variation was of the order of 400%. Results suggest that a large part of this variation is related to the Life Cycle Assessment methodologies applied, particularly in the end-of-life treatment, the use of credits for absorbed Carbon Dioxide, and the allocation of multifunctional process impacts. The feedstock source and processing method assumed for bio-based polymers was also a major sources of variation. The challenges of Life Cycle Assessment, particularly in a complex, geographically diverse and young industry like bio-based polymers, are recognised. It is proposed that the PEF standards should be adopted more widely in order to homogenise the methods used and allow meaningful comparison between LCA studies on fossil-based and bio-based polymers, and between studies of the same polymers.

Keywords

Bio-based polymers, Bioplastics, Life Cycle Assessment, Environmental Impact

1 Introduction

When Hermann Staudinger [1] postulated the existance of polymers in 1920, the world of materials changed forever. 'Plastic' has become a universal term encompassing the huge array of polymers now available, with wide-ranging chemical composition, mechanical properties, manufacturing methods and raw material feedstocks. Since 1950, an estimated 8.3 billion tonnes of plastic has been manufactured. The material class is found in almost every aspect of human life, and demand continues to grow. Plastic materials are undoubtedly useful, but in recent years the negative impact plastic can have on the environment and organisms living on earth has begun to be understood. This problem is exacerbated by the potential for polymers to leak from waste streams, or be lost as litter before reaching waste or recycling streams. This unmanaged waste can cause environmental and ecological damage, and poses further risks as it breaks down into smaller parts, known as microplastics, which can be mistaken for food by fish or animals, thereby entering food chains and potentially the human body. Alongside decarbonisation of energy supply and the adoption of renewable energy, plastic has become a focus of efforts to improve the sustainability of human life on earth, and a major campaign issue for environmental groups.

Partially in an attempt to address concerns over the rapid depletion of fossil resources, polymer manufacturers have recently developed polymers which use biological products as their feedstock. These products have been promoted as environmentally-friendly alternatives to traditional polymers, and have been adopted by some users looking to improve the environmental credentials of plastic products. However, the true environmental impacts of these products are not well understood. Extracting usable raw materials from biological products is not a trivial process, requiring significant energy input and producing waste. These additional stages of product development add to the total life cycle impact of the polymer, meaning that the resulting product may actually have a greater net environmental impact than the fossil-based polymer alternative. In order to address this concern, this study assesses and critically compares research carried out to date on the relative impacts of bio-based and fossil-based polymers over their full life cycle.

1.1 Aim

The aim of this study is to analyse the current state of the art in comparative Life Cycle Assessment of bio-based and fossil-based polymers, to:

- Assess similiarties and differences of existing reviews on the same polymers and the reasons behind any differences
- Identify any gaps in knowledge and data that need to be addressed to enable a comparative framework going forward
- Propose a way forward to enable accurate comparison of impacts of different polymers

2 Conceptual Framework

2.1 Fossil-based and Bio-based polymers

The vast majority of plastic products are fossil-based polymers, meaning they use resources derived from fossils as their feedstock. In the UK polymers are classified using the seven categories defined by the Society of the Plastics Industry: Polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polytheylene (LDPE), polypropylene (PP), polystyrene (PS), and 'Other', which includes polymers not classified in the previous categories. Global production of fossil-based polymers is of the order of 350 million tonnes per year.

While fossil-based polymers use fossil resources as their feedstock, bio-based polymers (often known as 'Bioplastics') use biological products as their feedstock. Though the term 'Bioplastic' is currently used to describe a variety of biologically-related products, this article uses the term to describe polymers manufactured using biological feedstock only[1].

Some bio-based polymers are chemically identical to fossil-based polymers, and are sometimes known as 'drop-ins', whereas others are entirely different polymers. Common bio-based polymers include polylactic acid (PLA), which may offer an alternative to polystyrene or expanded polystyrene; bio-based polyethylene terephthalate (Bio-PET), which is a direct replacement for fossil-based PET; and bio-based polybutylene succinate (Bio-PBS), which has similar properties to polypropylene.

[1] In addition to bio-based polymers, 'Bioplastic' is used to describe biodegradable and compostable polymers, regardless of the origin of their feedstock. It is suggested that the use of this terminology to describe all biologically-related polymers is misleading and likely to cause public confusion, and that the term should be restricted to polymers manufactured from biological feedstocks, but that discussion is outside the scope of this work.

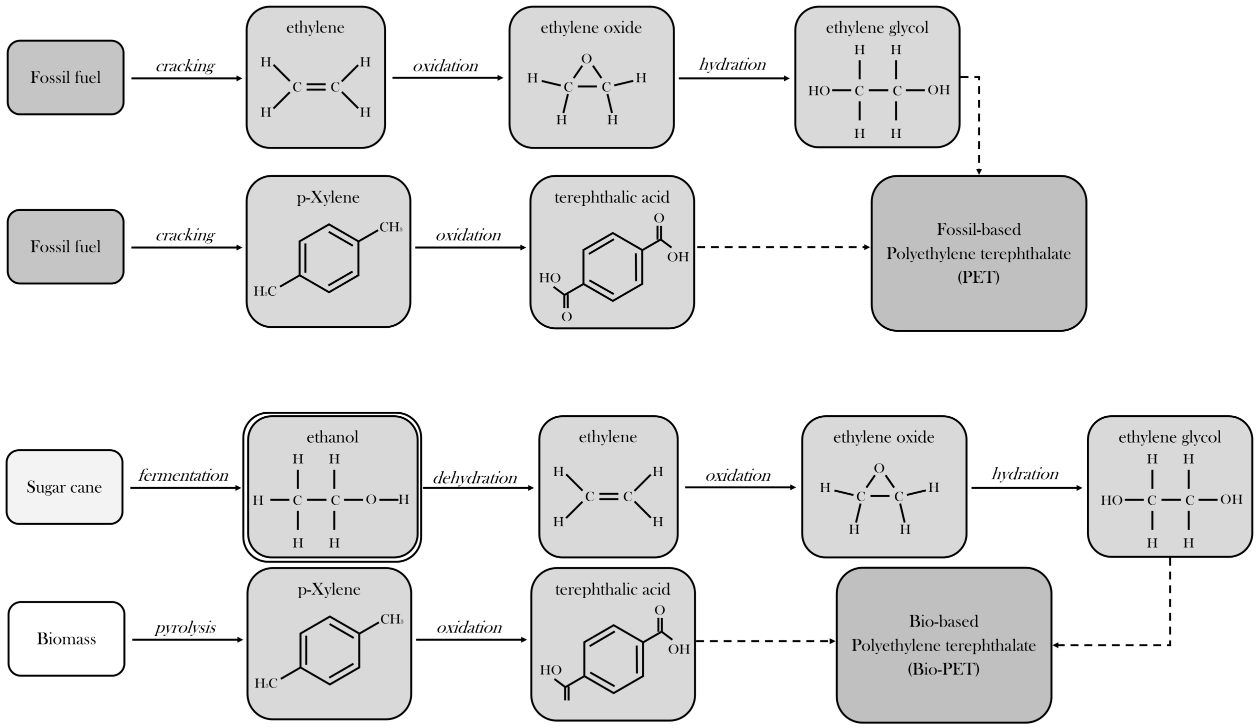

Figure 1: Example manufacturing process stages for fossil-based (top) and bio-based (bottom) PET

PET is one of the most commonly-used polymers, and in a fossil-based production scenario is made from terepthalic acid and ethylene glycol, both derived from the chemical cracking of fossil fuels. Bio-PET can be produced by the fermentation of sugarcane to produce ethylene glycol and the oxidisation of p-xylene from ligno-cellulosic biomass to produce teraphtalic acid. The manufacturing process diagrams shown in Figure 1 illustrate the similarities between the two processes, and highlight the additional processes required to produce Bio-PET.

Though the amount of carbon required to manufacture a given quantity of polymer is independent of the feedstock, since biological feedstock is created on a much shorter timescale than fossil fuel reserves, some consider bio-based polymers to be a form of carbon sequestration. This means that bio-based polymers can be said to have a lower feedstock carbon emission burden than fossil-based alternatives. However, they do not inherently avoid the potential ecological and environmental issues highlighted above, nor do they necessarily have lower lifetime carbon emissions, once energy required for manufacture, processing and end-of-life treatment are considered. Nonetheless, in the face of increasing consumer pressure to make environmentally positive changes, many industries where plastic packaging is used have begun to adopt bio-based polymers as an alternative to fossil-based polymers. The bio-based polymer industry is rapidly growing, with an expected 2020 market size of around 1.5 million tonnes [2], making it approximately 0.4% of the size of the current fossil-based polymer industry. The difference in scale of the bio-based and fossil-based polymer industries is an important consideration in this study, since emissions and environmental impacts per unit mass will change with the maturity and scale of the industry.

Claims of reduced environmental impacts, such as reduced contribution to global warming relative to fossil-based polymers, are often used to support the adoption of bioplastics as a sustainable alternative to fossil-based plastics. These claims are often unsubstantiated, and the long term sustainability of bio-based polymers across a full spectrum of potential impacts has only recently begun to be considered.

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method designed to assess the impacts of a product or process on the environment. When properly applied, Life Cycle Assessment allows the potential positive and negative impacts of a product, some of which would normally be invisible, to be estimated. By considering the upstream materials, processes, and sub-products which are necessary or unavoidable in the manufacture of a product, the impact of material and process choices can be assessed. By measuring the downstream impacts of the product, in use and at the end of life, it is possible to consider what impact the use, re-use, and ultimate disposal of a product has on the environment. Two types of study are commonly employed: Cradle-to-gate, which includes upstream impacts from raw materials to the point of a product leaving the manufacturer, and cradle-to-grave, which includes impacts from raw materials to end of life. Though a Life Cycle Assessment can never truly represent a real process to the absolute finest detail, the accuracy of an assessment hinges largely on the level of detail to which the upstream and downstream processes are studied, and the number of processes, related materials and products which are included. This detail encompases the accuracy of data, the allocation of burdens from sub-products and co-products (those required to manufacture the product, and those produced simultaneously, without which the central product cannot be manufactured), and the methodology used to translate this data into impacts. A wide range of impact assessment categories exist, ranging from well-known measures such as energy use or greenhouse gas emissions per unit of polymer production, to land or water use, acidification, eutrophication and further social or economic indicators. The selection of appropriate impact categories is critical to the production of a meaningful LCA. Numerous impact assessment methods exist, each of which specifies a series of impact categories, and defines the calculation method to be used in each case. This results in the potential for a given assessment to give different results when assessing the same product. A range of international standards (ISO14040 and 14044) exist for Life Cycle Assessment, but these do not prescribe the scope, data quality, assessment method or impact categories. In response to the proliferation of incomparable assessment methods, the European Union Product Environmental Footprint (EU PEF) method was developed. A similar method for organisational impact assessment (the OEF) was simultaneously created. Both methods are based on the previous International Life Cycle Data System (ILCD), and differ from other standards by prescribing in detail the method, impact categories, and requirements for data quality, among other requirements. Between 2013 and 2018 a pilot of the PEF was carried out, following which the method has now been published and made available for use [3].

2.3 Previous Literature Review

Published in 2018, *Bio-based plastics - A review of environmental, social and economic impact assessments* by Spierling et al. [4] reviewed bio-based polymers from social (S-LCA), economic (Life Cycle Costing, LCC) and environmental (LCA) perspectives. However, since social and economic comparisons were excluded early in the study due to a lack of suitable data, the work is effectively a review of LCA on bio-based polymers. The authors highlight the frameworks in place to support homogenaity across studies, specifically the ISO 14040/14044 standards, the International Life Cycle Data System, and EN 16760, which is a recent standard designed to supplement ISO14040/14044 for bio-material LCA. The ISO 14025 Product Category Rules (PCRs) and the Product Environmental Footprint (PEF) Product Category Rules are also discussed. Despite these aims to standardise LCA methods for bio-based products, the article found that environmental LCA results were only comparable in terms of global warming potential, and not across a greater range of impact categories. A total of 29 environmental studies were included in the review. Using these studies, the authors report a potential annual saving of 241 to 316 million tonnes of CO_2 eq available by replacing fossil-based plastics with bio-based plastics. However, the data used to give this value range incorporates data from studies employing different processes and standards, as is acknowleged in the article. The authors acknowledge the importance of use phase and end-of-life treatment, but due to the absence of studies providing full cradle-to-grave data, comparison between studies was done on a cradle-to-gate basis. This, alongside the differences in calculation method, and the fact that comparison was only possible for a single impact category, leaves a large gap in the comparison between fossil-based and bio-based polymers and makes it extremely difficult to draw conclusions with any certainty.

3 Methodology

It is clear that any meaningful review of LCA requires a large number of studies with the same scope, in order that comparison can be undertaken between multiple studies in more than one impact category. To find all relevant published work, a literature search was undertaken. This work focuses only on environmental LCA, enabling a greater number of relevant studies to be identified and reviewed, thus allowing a wider range of impact categories to be compared, and full cradle-to-grave impacts to be considered.

3.1 Literature Search Methodology

The search was undertaken using Google Scholar. Articles titles were searched using a range of search terms in order to find all articles describing comparative life cycle assessment of fossil-based and bio-based polymers. To try to ensure all relevant articles were included, a range of terms were used for each key word. For example, the search term 'bio-based polymer' was used, but was also replaced with other similar words, such as 'bioplastic' and 'biodegradable plastic'. Similarly, life cycle assessment was also searched for under the terms 'impact assessment' and 'eco-profile'. The search terms used were divided into three categories. The terms used in each category are illustrated in Figure 2. Category two and three describe the concepts mentioned previously, the form of plastic of interest to this study and the method of assessment, respectively. By combining each keyword in category two with each in category three, a large set of potential descriptions were produced. In some cases, an additional preceding keyword was required. Three were defined: 'Renewable', 'Compostable', and 'Biodegradable'. Each combination of keywords from category two and three was also tested without a preceding keyword, and with each of those mentioned above. Words where a hyphen or plural could be included were used with and without. This resulted in a total of 612 combinations (3 x 17 x 12).

In order to quickly search for these combinations, the OR Boolean was used to allow multiple searches to be conducted simultaneously. The 'allintitle:' search method was also used, meaning that a specific word order was not required. These results were individually reviewed and those which transpired to be not relevant were removed. In many cases, the use of these terms in the title had been used to describe the development of manufacturing processes. After the removal of those which did not include environmental Life Cycle Assessment, 56 articles remained, with the earliest dating from 1999.
Articles were published by authors working across the world, with most articles from authors in Europe, followed by the Americas and Asia. The temporal spread of articles and the most common journals are shown in Figure 3. As illustrated, the most popular journal was the *The Journal of Cleaner Production*, within which 10 relevant articles were found. The 'Other' bar indicates the sum of journals in which only one relevant article was published.

One of these articles [4] is itself a review article. This article references 29 environmental life cycle assessments, all but one of which were found in the literature search. This article could not be located, so was not included.

3.2 Critical Review Method

As acknowledged by Spierling et al [4], (*'further alignment of joint frameworks and therein guidance regarding critical issues for the assessment of biobased plastics is needed in order to enable meaningful comparisons'*), a key step towards comparable LCA results is the development of standards. To assess the similarity of scope of various studies, a critical review method was developed to determine the level of compliance of an LCA study with the EU PEF standards. The PEF standards [3] list nine mandatory requirements, two recommended requirements and one optional requirement. The requirements of the PEF standard are illustrated in Figure 4. Since the articles in question deal with comparisons between fossil-based and bio-based plastic, the lower row ('B2B / B2C with comparisons / competative assertions') is the relevant one.

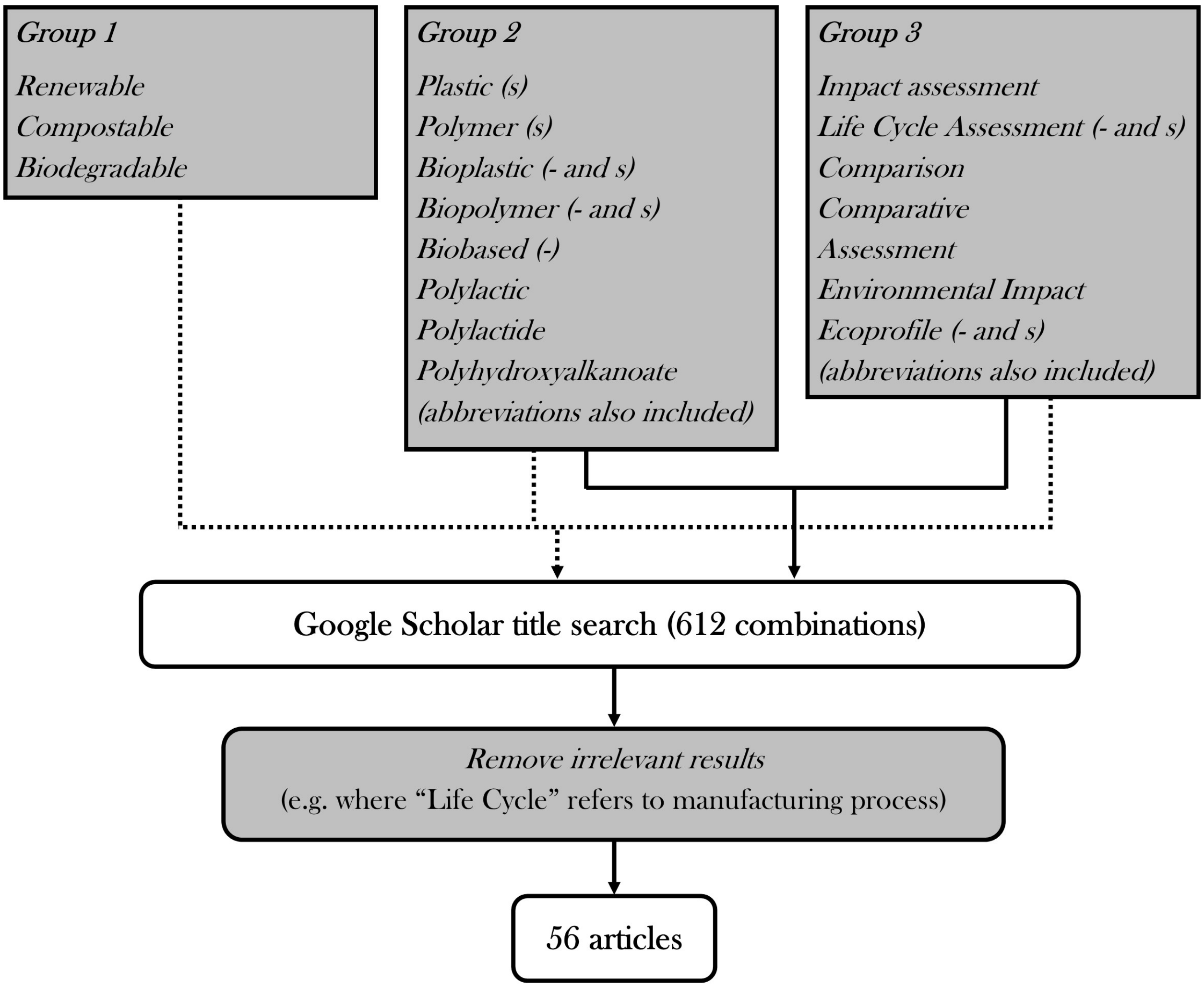

Figure 2: Structure and search terms used in Bioplastic LCA literature search

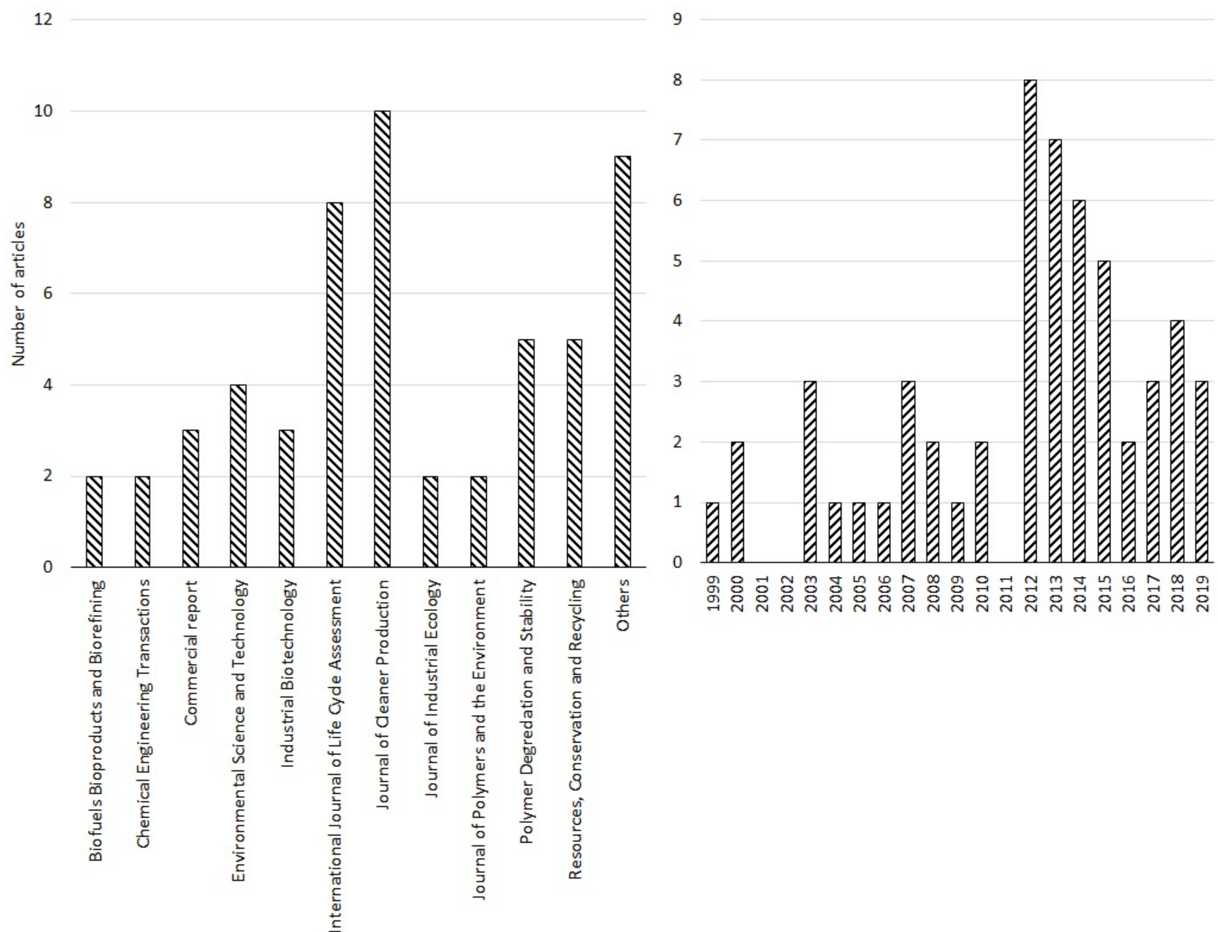

Figure 3: Spread of journal (l) and publication date (r) for 56 articles included in the review

In order for a research article to be classified as a comparitive LCA, it is required to demonstrate all the mandatory attributes required by the PEF standard, and to cover a cradle-to-grave life cycle, including use and end-of-life phases. These were felt to be the minimum standards for a comparitive LCA, and that these standards are required in order to allow fair comparison between studies. Each of the 56 research articles puporting to describe comparitive LCA between fossil-based and bio-based plastics were compared to these standards, and only those which met them were classified as full comparitive LCA studies.

3.3 Mandatory requirements of Product Environmental Footprint method

Using the PEF guidance, a brief description of our interpretation of each mandatory requirement into a standard practically applicable to a journal article is given below. The guidance offers a great deal more insight into each category, so only the initial definition is given here.

3.3.1 Goal & Scope

PEF guidance states that *'it is important to identify the intended applications and the degree of analytical depth and rigour of the study'*. Furthermore, the guidance states that the goal definition of a PEF-compliant study should include the following six elements: *Intended application(s)*; *reasons for carrying out the study*

Intended applications		Goal & Scope definition	Screening exercise	Meet data quality requirements	Multifunctionality hierarchy	Choice of impact assessment methods	Classification & Characterisation	Normalisation	Weighting	Interpretation of PEF results	Reporting element requirements	Critical review (1 person)	Critical review panel (3 persons)	Requires PEFCR
External	B2B/B2C without comparisons/comparative assertions	M	R	M	M	M	M	R	O	M	M	M	R	R
	B2B/B2C with comparisons/ comparative assertions	M	R	M	M	M	M	R	O	M	M	/	M	M

"M" = mandatory;
"R" = recommended (not mandatory);
"O" = optional (not mandatory);
"/" = not applicable

Figure 4: PEF rules for comparative LCA studies (from [3])

and decision context; *target audience*; *whether comparisons and/or competitive assertions are to be disclosed to the public*; *commissioner of the study*; and *review procedure*. Where a study included all these elements, it was defined as meeting the Goal & Scope requirement. Where a study met four or more elements, it was defined as partially meeting the requirement.

3.3.2 Meet data quality requirements

To meet the PEF requirements for data quality, data should exhibit: *Technical appropriateness*; *Geographical appropriateness*; *Time-related appropriateness*; *Completeness*; and *Precision*. Each category can be scored numerically, where data is marked from *Very Good*, requiring data with at least 90% completeness, and context-speficic technical, geographical and temporal appropriateness, to *Very Poor*, with completeness of less than 50% and high levels of uncertainty. In each category, a score for *Data Quality Rating* (DQR) is given based on the closest matching description as given in the guidance. This gives a rating between 1 (Very Good) and 5 (Very Poor). Once each category (Technical appropriateness, etc. as given above) has been scored, a total DQR can be calculated by summing the six individual categories, and dividing by 6. This gives a final rating from *Excellent* to *Poor*, as described in Table 1. A rating of Excellent or Very Good was defined as meeting the PEF data quality requirement, and a rating of Fair or Good as partially meeting the requirement.

3.3.3 Multifunctionality hierarchy

If a process or facility provides more than one function, it is defined as multifunctional by PEF rules. In the case of product production, additional products are known as co-products. To correctly represent this process in LCA requires a Multifunctional heirarchy, which partitions inputs and emissions linked to the process between resulting products. Inputs and emissions should be allocated based on subdivision or

Table 1: Total Data Quality Rating (DQR) score and level

Overall data quality rating	Overall data quality level
1.6 or below	Excellent
1.6 to 2.0	Very Good
2.0 to 3.0	Good
3.0 to 4.0	Fair
above 4.0	Poor

system expansion as the first preference. Subdivision is preferred where the multifunctional process can be simply divided into its constituent sub-processes, and each of these treated as an individual process. System expansion involves expanding a system to include the complete functions of a co-product. If neither subdivision or system expansion are possible, the next step down the hierarchy is *Allocation based on an underlying physical relationship*. This method allows the use of a relationship between product inputs and co-product outputs. PEF guidance suggests that such a relationship is be based on *'a physical property of the inputs and outputs that is relevant to the process provided by the co-product of interest'*. If allocation by this method is not possible, then the final step on the hierarchy may be used: *Allocation based on some other relationship*. The commonest example of this method of allocation is perhaps the use of economic value of products and co-products as the allocation method. The use of subdivision or system expansion was required in order to class a study as meeting the requirement, and allocation by an underlying physical, or other, relationship to partially meet the requirement.

3.3.4 Choice of impact assessment methods

The PEF method requires that the Evironmental Footprint (EF) impact assessment methods are used, unless a specific reason can be given for the exclusion of a category. The categories included in the EF method are: Global warming, Ozone depletion, Ionising radiation, Ozone formation, Fine particulates, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Ecotoxicity, Human toxicity, Land use, Mineral resource, Fossil resource, Water use. A study was defined as meeting this requirement if it included all these categories, or as partially meeting it if at least half were included.

3.3.5 Classification & Characterisation

The PEF method requires that classification and characterisation steps are undertaken. Classificiation describes the assignment, following the Life Cycle Inventory Assessment phase, of input and output results to categories in the Environmental Footprint impact assessment method. Characterisation refers to the calculation of the magnitude of contribution of each input or output to its respective EF categories. Characterisation factors developed for use in the PEF method are available in the guidance [3]. To meet this requirement, studies were required to include both classification and characterisation. If only classification was included, the requirement was partially met.

3.3.6 Interpretation of PEF results

The interpretation of results required by the PEF method has two subsets: The first is based on the defined goal and scope of the project, and is a check to confirm that this has been met. If this scope has not been met, the PEF suggests an iterative method should be adopted until the initial scope is met. The secondary aim of the interpretation section is to assess the robustness of the method adopted and the conculsions drawn. The method suggests three tools which can be used to assess the robustness of the model: Completeness checks, Sensitivity checks, and Consistency checks. Completeness checks assess the resource use and emissions profile data used, with the aim of comparing this to the scope and definition of the project to confirm suitability. Sensitivity checks aim to test the impact of alternative choices. Consistency checks aim to confirm that the same assumptions, methods and data quality considerations have been applied throughout the study.

In each case, if the check has been implemented and results presented, the check is classed as met. The Interpretation of results requirement is classed as met if the goal check and all three robustness checks are included, and partially met if at least two of the four are met.

3.3.7 Reporting element requirements

This section of the requirements describes the key elements of a PEF reporting system. Peer-reviewed journal articles are likely to satisfy these requirements. The requirements stipulate three key areas: A summary (which must constitute a standalone summary of the work), the main report (which must include: Goal, Scope, Compilation of resource use / emission profile, Calculation of PEF impact results, Interpretation of results), and at least one annexe, primarily containing descriptions of assumptions. The summary section is likely to be satisfied by the abstract of a journal article, and in some cases the main report may itself contain all the details suggested for inclusion in the annexe. This requirement is defined as met if all three sections are included, and partially met if two are included.

3.3.8 Critical review panel (3 persons)

For a review with a comparitive element, the PEF guidance requires review to be undertaken by three 'suitably qualified' reviewers. The guidance document gives details of how such a person may be defined via a scoring matrix which equates years of experience to a numerical score. Each reviewer must achieve at least six points. Articles submitted for peer-reviewed publication are likely to be reviewed by at least 3 people before publication, and it is expected that these reviewers will meet the six point threshold, which for example requires 3-4 years of LCA practice and article review, 3-5 years of related experience, and a review history of 6-15 articles (this is an example of how at least six points could be scored, there are numerous other combinations to achieve the same score). This requirement was deemed to have been met if reviewed by at least three six-point reviewers prior to publication, and partially met if reviewed by fewer, or by three reviewers scoring less than six points.

3.3.9 Requires PEFCR

This final mandatory section requires the use of PEF Category Rules (PEFCR), if relevant Category Rules (CRs) exist. CRs are specific rules for LCA of particular product families, and are developed by committees of interested and knowledgable parties. Where a PEFCR exists for the product being studied, they give more specific requirements than the general PEF guidance ans should be used in preference. New CRs are constantly in development, but at present no PEFCRs exist for bio-based polymers. Though a set of PEFCRs do exist for bottled water, which includes packing and specifically discussed PET bottles, the requirements in this aspect are no different to that of the general PEF guidance.

4 Results & Discussion

4.1 Research Articles

Each of the 56 research articles identified were compared to the mandatory PEF criteria described above, and were defined as either meeting (Y), partially meeting (P), or not meeting (N) the standards defined in each category. The results of this analysis are given in Table 2. It is also noted (in the 'Type' column) in each case whether the article in question was a cradle-to-gate (Gate) or cradle-to-grave (Grave) study. Studies were excluded at this stage which did not achieve a total of two 'Y' results, or one 'Y' and two 'P' results. Only studies which were taken forward to further consideration are included in Table 2.

Table 2: Comparison of identified articles to PEF mandatory requirements

Author	Type	Goal & Scope	Data	Multifunc.	IAM	Clas. & Char.	Interp.	Reporting	Review	PEFCR
Alvarenga 2013 [5]	Gate	Y	P	Y	Y	Y	Y	Y	Y	N
Bohlmann 2004 [6]	Grave	Y	P	P	N	N	Y	Y	Y	N
Chen 2016 [7]	Gate	Y	P	Y	P	P	P	Y	Y	N
Groot-Boren 2010 [8]	Gate	Y	N	Y	P	Y	Y	Y	Y	N
Harding 2007 [9]	Gate	Y	P	N	P	P	N	Y	Y	N
Haylock 2018 [10]	Grave	Y	P	N	P	N	Y	Y	Y	N
Hottle 2013 [11]	Grave	Y	P	-	P	-	Y	Y	Y	N
Hottle 2017 [12]	Grave	Y	P	Y	P	Y	Y	Y	Y	N
Kim-Dale 2005 [13]	Gate	Y	P	Y	P	P	Y	Y	Y	N
Kim-Dale 2008 [14]	Gate	Y	P	N	N	N	P	Y	Y	N
Koch 2018 [15]	Gate	Y	P	N	N	N	N	Y	Y	N
Kookos 2019 [16]	Gate	Y	P	P	N	N	N	Y	Y	N
Kurdikar 2000 [17]	-	Y	N	Y	N	Y	P	Y	Y	N
Leceta 2014 [18]	Grave	Y	P	Y	P	Y	N	Y	Y	N
Maga 2019 [2]	Grave	Y	P	Y	Y	Y	P	Y	Y	N
Mahalle 2014 [19]	Gate	Y	P	P	P	Y	P	Y	Y	N
Papong 2014 [20]	Gate	Y	N	P	P	P	Y	Y	Y	N
Petchprayul 2012 [21]	Grave	Y	N		N	N	N	Y	Y	N
Posen 2016 [22]	Gate	Y	P	Y	N	N	Y	Y	Y	N
Potting 2015 [23]	Grave	Y	P	Y	P	Y	Y	Y	Y	N
Rostkowski 2012 [24]	Gate	Y	N	N	P	N	N	Y	Y	N
Shen 2012 [25]	Grave	Y	P	Y	N	Y	Y	Y	Y	N
Spierling 2018 [4]	Gate	Y	P	Y	N	Y	Y	Y	Y	N
Taengwathananukool 2013 [26]	Grave	Y	N	N	P	Y	N	Y	Y	N
Tsiropoulos 2015 [27]	Gate	Y	P	Y	P	N	N	Y	Y	N
Vidal 2007 [28]	Grave	Y	N	P	P	Y	P	Y	Y	N
Vink-Davies 2015 [29]	Gate	Y	N	N	P	P	N	Y	Y	N
Ziem 2013 [30]	Gate	Y	N	P	P	N	P	Y	P	N

Of the articles listed in Table 2, it was not possible to extract accurate data from three (Leceta 2014[18], Maga 2019[2] and Potting 2015[23]) due to the presentation methods used, leaving 25 studies, from which 89 separate polymer results (50 bio-based and 39 fossil-based) were obtained. These LCA results were compared in order to investigate the level of agreement between studies. Although no studies were found to be fully compliant with the PEF method, many authors highlighted that their studies were carried out to ISO14040 and 14044 standards, so a degree of agreement between studies for the same case and type could be expected. A range of impact assessment categories were used across the studies. Only two studies were fully compliant with the PEF categories, but many studies included categories such as Energy use (MJ/functional unit) and CO_2 emissions (kgCO_2 eq/functional unit). Comparative results are shown in figures 5 to 11. Figures were generated for impact categories in which data existed for 10% or more of data sets. Using this criteria, results for the following categories are given: Energy use (MJ/kg polymer), Ecotoxicity (CTU_e/kg polymer), Acidification (kgSO_2 eq/kg polymer), Eutrophication (kgPO_4 eq/kg polymer), Climate change (kgCO_2 eq/kg polymer), Particulate matter formation (kgPM2.5-10 eq/kg polymer), and Ozone depletion (kgCFC_{11} eq/kg polymer). Results are shown for both cradle-to-gate and cradle-to-grave studies, with the former indicated by filled markers and the latter by open markers in all cases.

4.2 Comparison of Fossil-based and Bio-based polymers

The clearest result from the collected data presented in these figures is the lack of agreement between studies. Perhaps surprisingly, this is exhibited in fossil-based polymer results as well as in bio-based polymer results. For example, data for cradle-to-grave energy use in fossil-based PET (see Figure 5) shows variation of over 400% between results. In other impact categories there appears to be a greater concensus, for example in the climate change and eutrophication categories, data for fossil-based HDPE shows reasonable agreement between studies (see Figure 9 and Figure 8 respectively).

Comparing fossil-based to bio-based polymers is challenging given the spread of data in most cases. The prevailing scientific concensus to date has been that whilst bio-based polymers can achieve better results than fossil-based polymers in climate change and energy use categories, full LCA tends to reveal that they are outperformed by fossil-based polymers in impact categories such as eutrophication and acidification. Due to the significant ranges in data values in every impact category, the data presented here is unable to reliably support this hypothesis. In energy use and climate change categories, fossil-based and bio-based polymers show very similar data ranges. In acidification, bio-based PBS and PET score badly, and in particulate matter formation, bio-based PET, PHB and PVC are reported as significantly worse than alternatives. In ecotoxicity, bio-based PET was reported to have potential over twice that of fossil and bio-based alternatives. In eutrophication, bio-based PLA and other polymers both exhibit values over twice that of fossil and bio-based alternatvies. Some results presented here (e.g. results for PET in Figure 9, where bio-based and fossil-based PET show similar results) appear to suggest that variation between polymers is more prominent than variation between fossil or biological feedstock. Climate change results showed a number of negative results in bio-based polymer cases. This is due to the crediting of CO_2 absorbed by biomass during its growth to the polymer product. This is a controversial and potentially misleading method when used in cradle-to-gate studies where the end of life emission of CO_2 is not included, or when used in comparative studies, since the CO_2 absorbed by biomass which ultimately became the fossil resource used to create fossil-based polymers is not included.

Since the variation between studies does not allow comparison between fossil-based and bio-based polymers, other differences between cases have not yet arisen. However, future studies on the subject should consider the maturity gap between fossil-based and bio-based polymer industries. Fossil-based polymer production methods are well-established and benefit from years of development to improve efficiency, which are not yet in place in the bio-based polymer industry. The potential for efficiency improvement in the bio-based polymer manufacturing industry should be considered in any environmental impact projection.

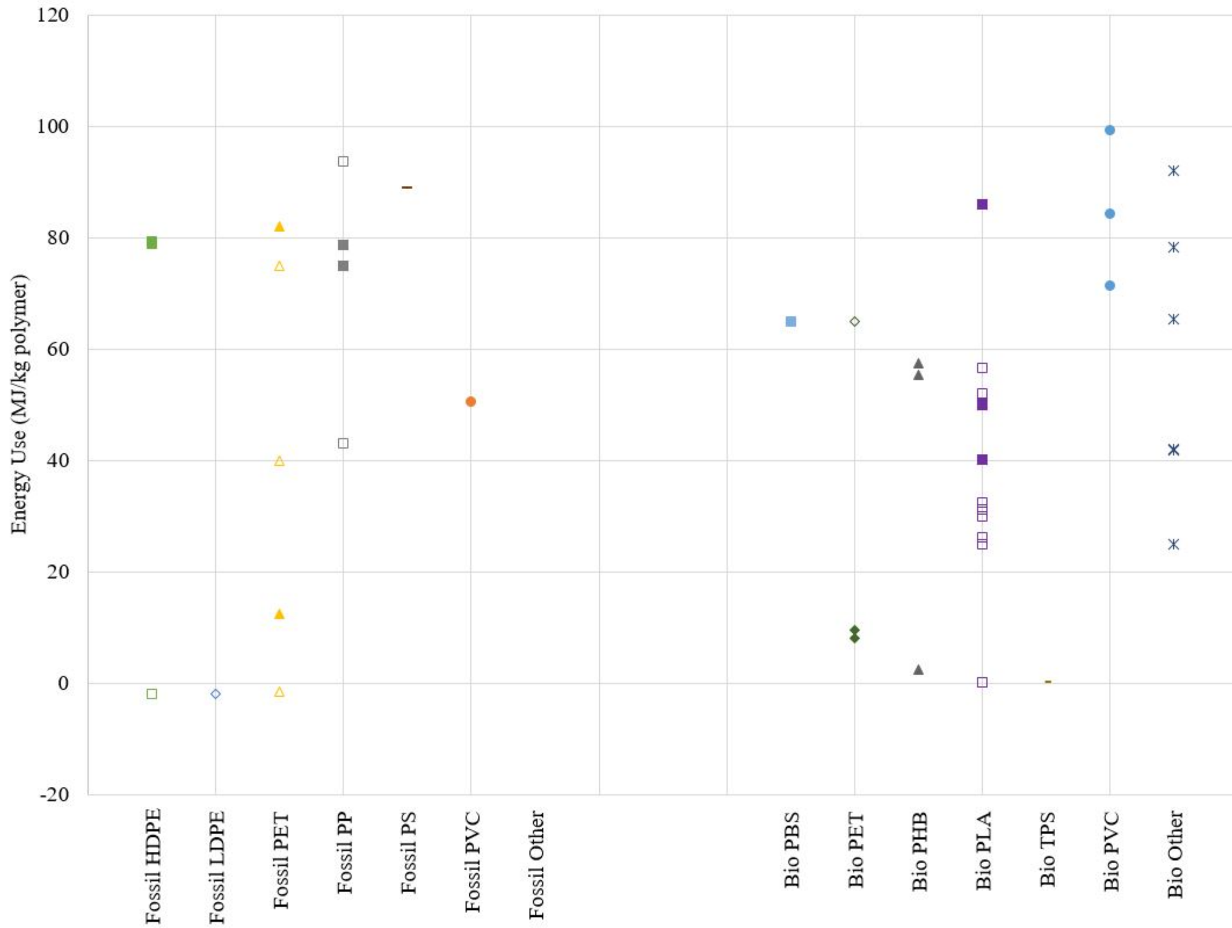

Figure 5: Energy use (MJ/kg) data for fossil-based and bio-based plastics. Collected results from 43 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

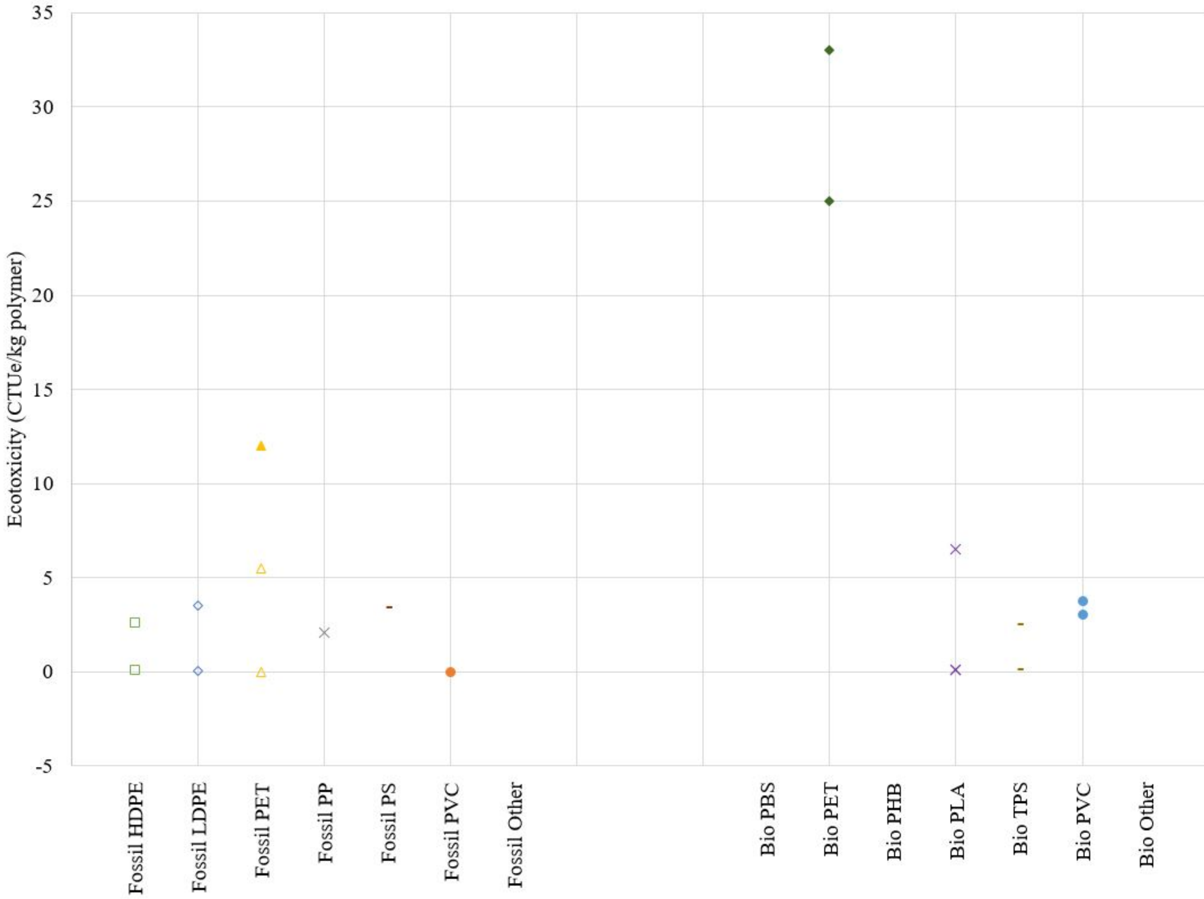

Figure 6: Ecotoxicity (CTU_e/kg) data for fossil-based and bio-based plastics. Collected results from 18 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

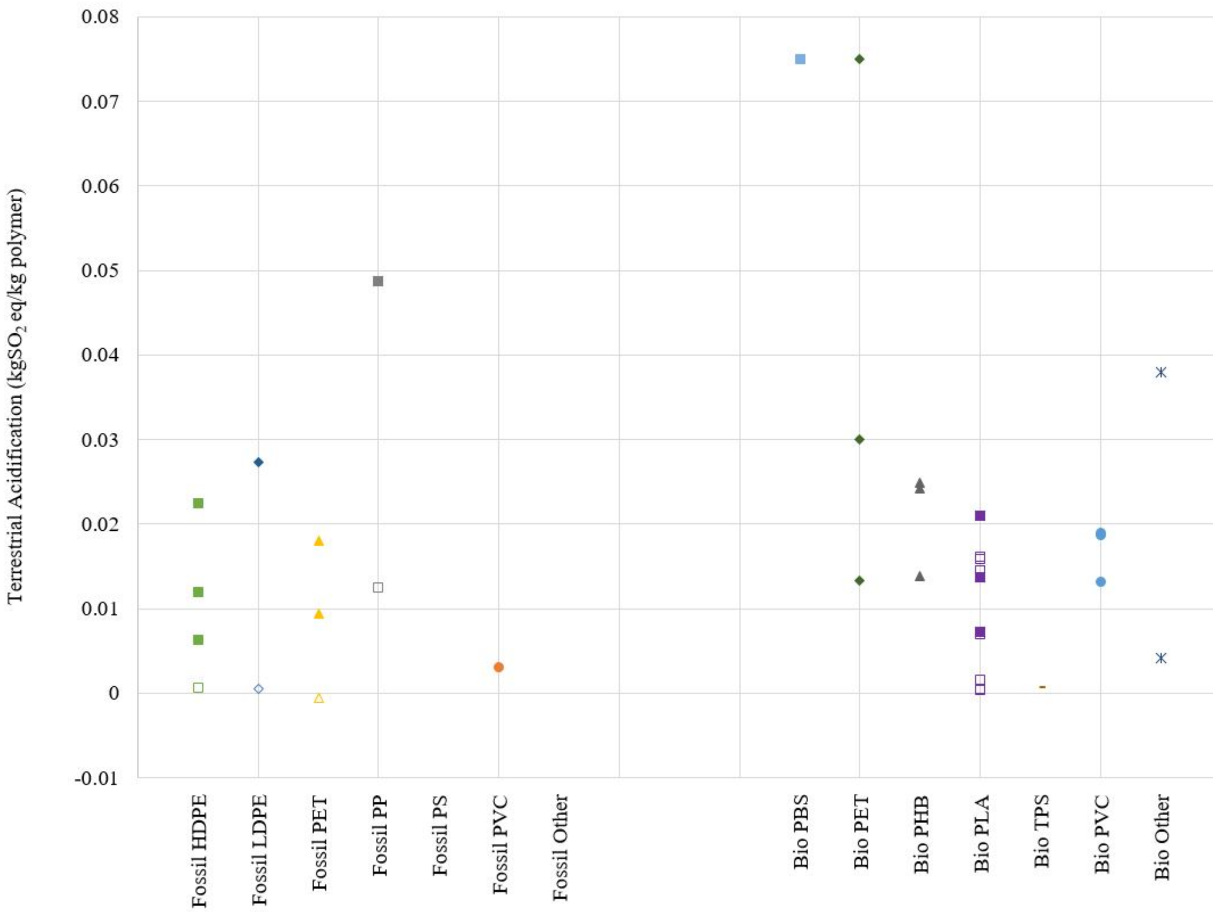

Figure 7: Acidification (kgSO$_2$ eq/kg) data for fossil-based and bio-based plastics. Collected results from 35 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

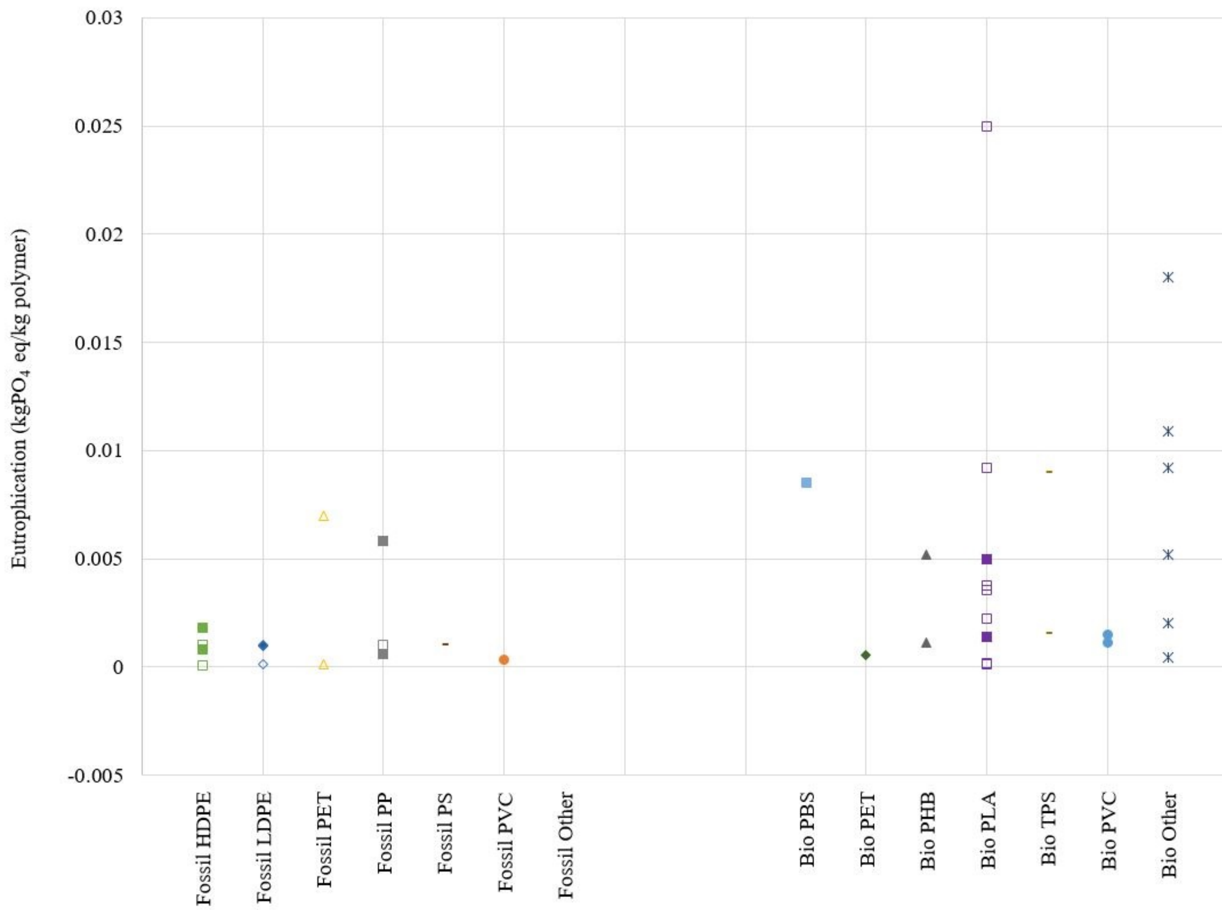

Figure 8: Eutrophication (kgPO$_4$ eq/kg) data for fossil-based and bio-based plastics. Collected results from 35 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

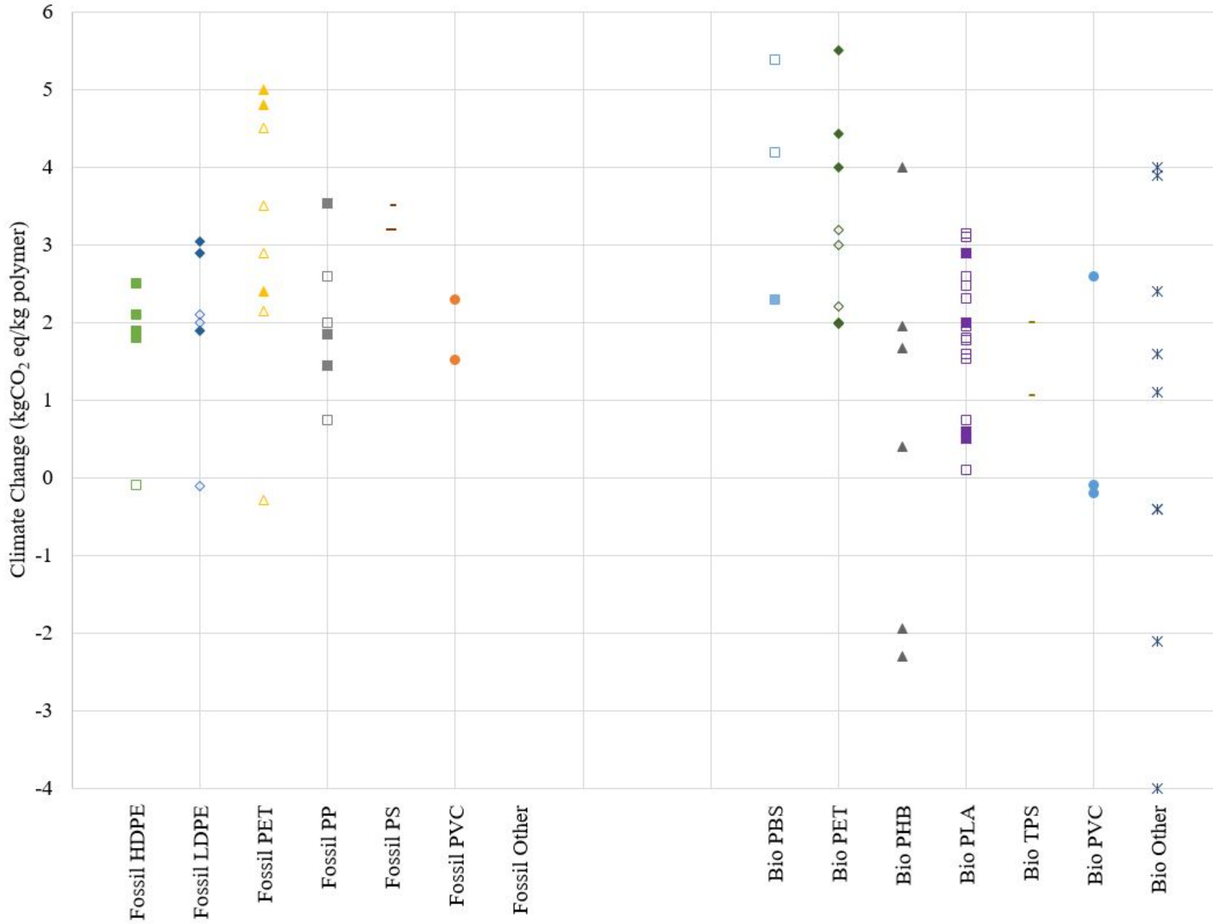

Figure 9: Climate Change ($kgCO_2$ eq/kg) data for fossil-based and bio-based plastics. Collected results from 87 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

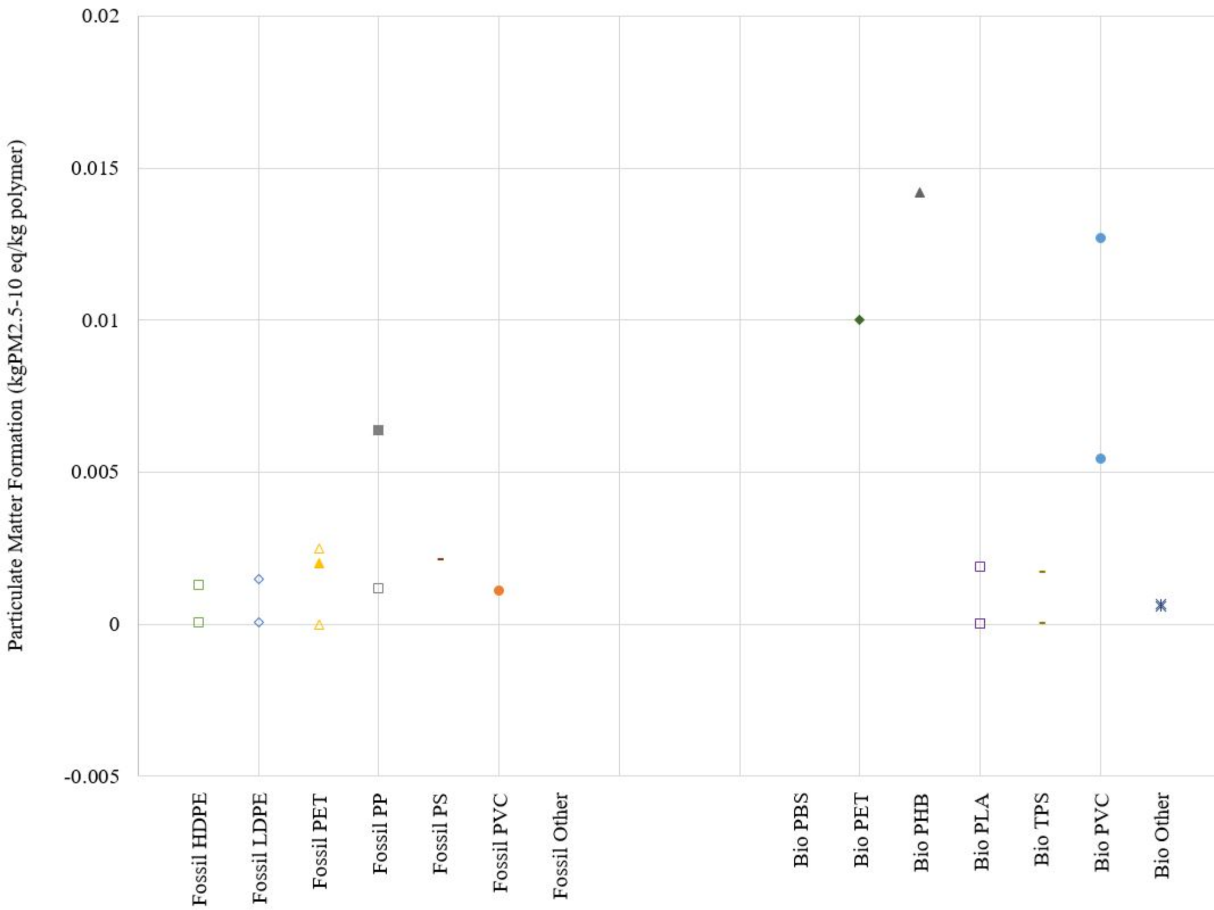

Figure 10: Particulate matter formation (kgPM2.5-10 eq/kg) data for fossil-based and bio-based plastics. Collected results from 21 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

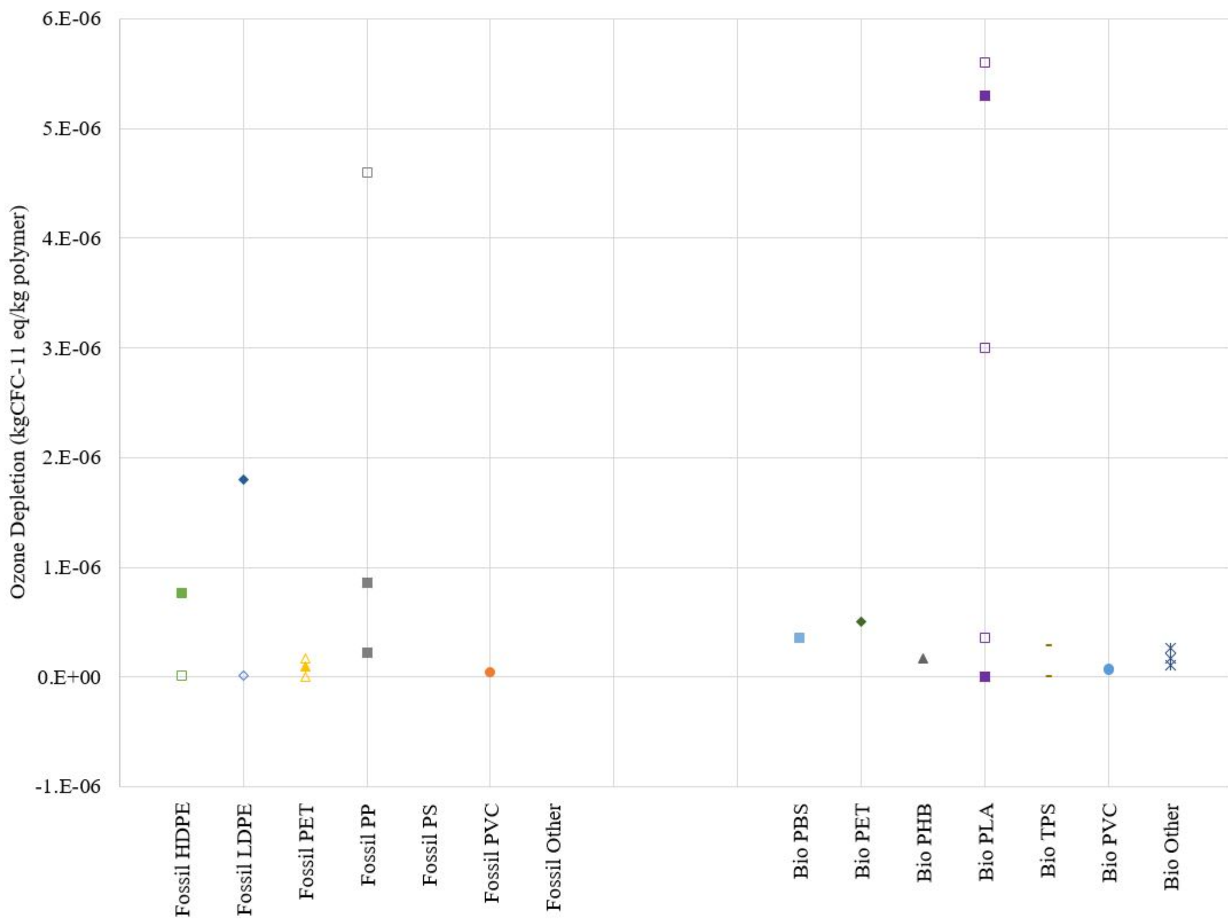

Figure 11: Ozone depletion (kgCFC$_{11}$ eq/kg) data for fossil-based and bio-based plastics. Collected results from 26 studies. Filled markers and wider dashes indicate cradle-to-gate studies, open markers and short dashes indicate cradle-to-grave studies.

4.3 Impact category results

In energy use, the lowest cradle-to-grave values observed were for Bio PET and Bio PHB, which were reported to use between 3 and 10 MJ/kg of polymer. Fossil-based polymer data showed a cluster of results around 80 MJ/kg, with HDPE, PET, PP and PS all being in this region. Bio-based polymers such as PBS, PHB and bio-PVC were reported to have similar results, whilst PLA showed a wide spread between 40 and 90 MJ/kg. In all cases, the spread of data is a cause for concern, and results should be treated with caution.

Ecotoxicity and acidification results were generally higher for bio-based polymers, particularly in the bio-based PET case, which showed results 100% worse than the worst performing fossil-based polymer in ecotoxicity, and 60% worse than the worst performing fossil-based polymer in acidification. Bio-based polymers were also reported as performing worse than fossil-based polymers in eutrophication, with PLA and 'Other' bio-based polymers performing worst of all. The 'Other' category includes bio-based polymers for which only one result was reported (PHA, PP, PPT, HDPE), or the specific polymer name was not given in the literature.

Particulate formation and ozone depletion results were reported in fewer studies than the other impacts. In the former case, cradle-to-grave studies show much higher values of particulate formation than cradle-to-gate studies, reflecting the emission of particulates during end-of-life incineration in some cases. This highlights a further source of variation between the studies, with some reporting multiple end-of-life treatments. In most bio-based polymer cases composting was assumed, but replacing this with incineration increases particulate emissions significantly. In the ozone depletion category, PLA was found to perform particularly badly, with depletion values of more than 10 times those of most other polymers. Fossil-based PP also performed badly when considered over its full lifetime.

4.4 Comparison within impact categories

In the majority of impact categories illustrated in Figures 5 to 11, bio-based PET appears to perform worse than almost any other polymer. The variation observed between bio-based PET results and other bio-based and fossil-based polymers could be for one of three reasons: (1) bio-based PET studies considered factors which other studies ignored, which have a negative effect; (2) other studies considered factors which bio-based PET studies ignored, which have a positive effect; or (3) bio-based PET does indeed perform worse than other polymers in these measures.

Three impact categories in which bio-based PET showed significantly greater values than all or nearly-all other polymers were acidification, particulate matter formation, and ecotoxity. Data for bio-based PET was taken from seven results: Three cradle-to-gate (two results published by Chen in 2016 [7] and one by Koch in 2018 [15]) and four cradle-to-grave (two published by Shen 2012 [25] and two by Tsiropoulus in 2014 [27]). However, data for these categories was reported only by cradle-to-gate studies, in the case of acidification by Chen [7] and Koch [15], and for particulate matter formation and ecotoxicity by Chen [7] only. This study scored relatively well in the critical review, achieving four full compliance points and four partial compliance points from nine measures.

As discussed earlier in this article, PET is made from teraphthalic acid and ethylene glycol. Both intermediate products can be made from biologically derived products. In the work by Chen, terephthalic acid was produced from either wood or corn stover (giving the two cases included in the results), and ethylene glycol was derived from corn (though in most cases, replacing corn with wheat straw yielded the same results).

As well as Chen [7], acidification was also included as an impact category in a cradle-to-gate study by Koch [15], who reported a value of 0.0133 $kgSO_2$ eq/kg, compared to the Chen values of 0.03 $kgSO_2$ eq/kg and 0.075 $kgSO_2$ eq/kg for wood-based and corn stover-based terephthalic acid respectively. Comparison of the two studies using Table 2 reveals that the former was less compliant with the PEF method, since it did not achieve the required standards in Multifunctional Heirarchy, Impact assessment method, Classificiation and Characterisation, or Interpretation of results. Of these, Multifunctional Heirarchy and Classification and Characterisation are the most likely to impact results. Further analysis of results in other polymer cases (for example Fossil HDPE, Fossil PET, and Bio PLA) suggests that studies which did not meet the PEF standard for Multifunctional Heirarchy or Classification and Characterisation calculated lower values of Acidification compared to those that did meet the standards. This suggests, perhaps, that the values proposed by Chen [7] may be the more realistic of the two result cases. However, it is very difficult to conclude with a high level of certainty that the value proposed by Chen should be assumed definitive. If further studies conducted indepentently and to the same standards provided similar results, this would improve the validity of the result.

In order to investigate this potential correlation between low compliance with the PEF standard and underprediction of impact category results, each study was given a numerical PEF compliance score based on the data in Table 2 ('Y' = 2, 'P' = 1, 'N' = 0). This measure was calculated for all 89 result cases and was plotted against standard deviation from the mean value of each impact category result. The results were inconclusive, with some impact categories showing an increasing trend (correlation between high PEF score and high impact category score), some showing the opposite, and some no trend at all. This data is shown in Figure 12 and further highlights the incompatibility of the studies.

4.5 A way forward

As stated in Section 1.1, the final aim of this work is to *propose a way forward to enable accurate comparison of the environmental impact of different polymers*. The comparative analysis of studies described in this article suggests that methodological differences between studies may be the underlying cause of variation in results. We therefore suggest that in addition to ensuring compliance with the relevant ISO standards, authors of comparative Life Cycle Assessment studies should comply with every section of the EU Product Environmental Footprint method. We emphasise the importance of compliance with every section of the standard since, as shown in Figure 12, even compliance with nearly all sections does not appear to correlate with a narrowing of the range of predicted values. In order to allow simple and reliable comparison of studies, we also suggest that wherever possible, authors publishing comparative Life Cycle Assessment studies include specific details of their compliance with each section of the PEF method.

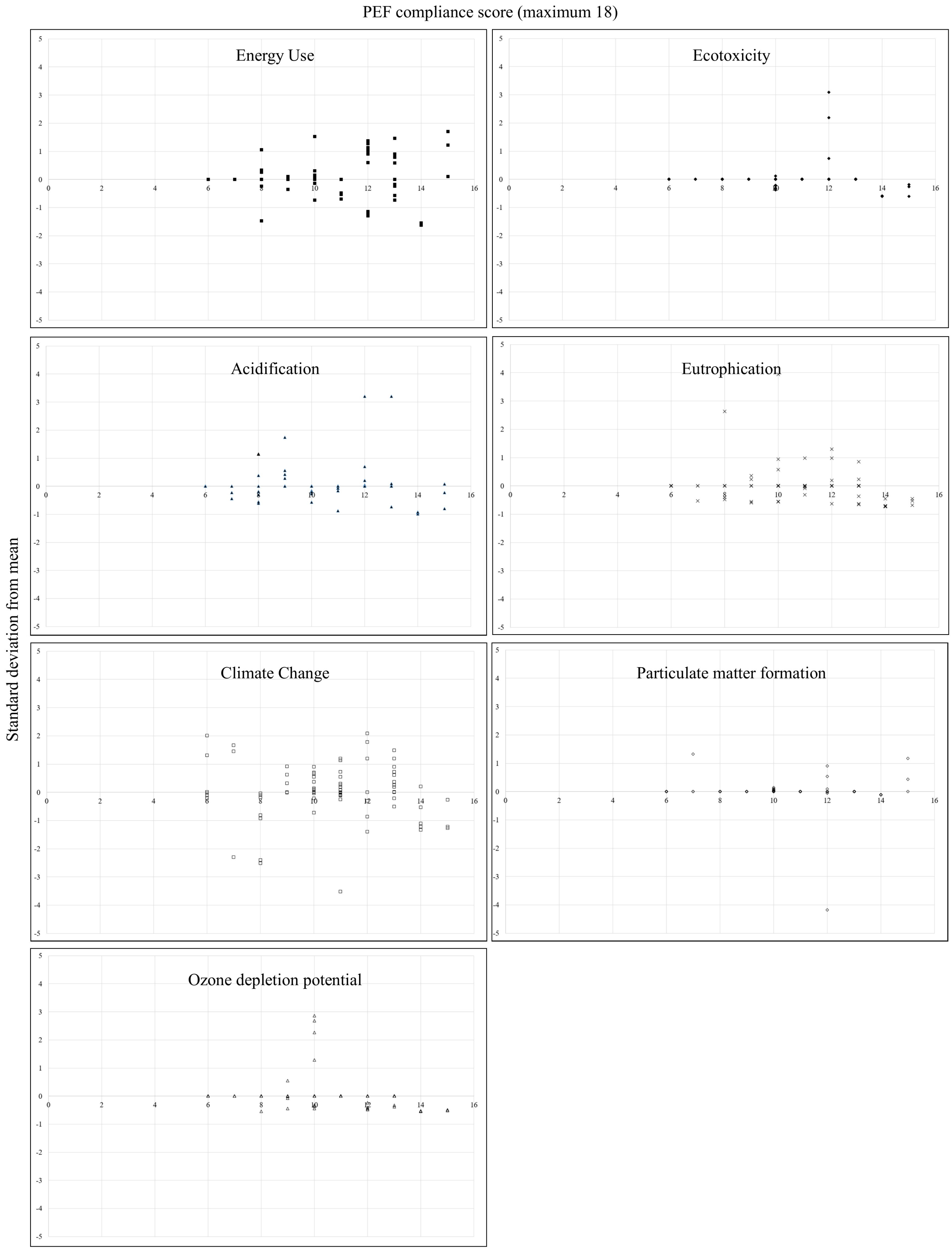

Figure 12: Comparison of PEF compliance score (from a maximum of 18) with standard deviation from mean of results in each impact category

5 Conclusion

Results from published Life Cycle Assessment studies of 50 bio-based polymers and 39 fossil-based polymers were compared. Across the seven impact categories for which sufficient data was available, results showed significant variation in impact between polymers, both between fossil-based and bio-based categories, between individual polymers within each category, and between different studies of the same polymer. Variation in results of the order of 200% to 400% was observed between studies of the same polymer with the same scope. In some cases the differences between results for the same polymer and scope were very large, for example ozone depletion for cradle-to-gate studies of PLA, where maximum reported values were over 1000 times greater than minimum reported values.

Due to the variation in methodology between studies it is impossible to know whether these differences indicate genuine variation in the environmental credentials of polymers, or are indicative of the different assessment methods used. It is therefore not possible to highlight 'best performing' polymers, or to suggest whether fossil-based or bio-based polymers perform best in any impact category. Further investigation into detail not provided in published literature would be needed to further investigate this.

Studies were assessed using a critical review method based on the EU Product Environmental Footprint standard. No study achieved full compliance with the standard, and though it was possible to rank studies in order of the degree to which they did comply, this showed no correlation with results in any impact category. A significant proportion of studies were not compliant with key parts of the PEF method, such as the treatment of co-products and multifunctional hierarchy, impact classification, and impact characterisation. Without the ability to compare across studies, LCA has much lower relevance than it could or should have.

In light of the ongoing growth in the adoption of bio-based polymers, comparative Life Cycle Assessment of the environmental impact of bio-based and fossil-based polymers is urgently required. There is a great danger otherwise of action being taken which leads to unintended and potentially undesirable consequences. Without this information it is not possible to consider the important balances and trade-offs between polymers and between impacts, which are essential in sensible material selection. In order to conduct this work within a standard framework, and therefore ensure comparability between studies, it is suggested that the EU PEF standard is adopted and adhered to in full. In order to understand the implications of bio-based polymers on the end of life treatment of products, it is suggested that a cradle-to-grave scope is used wherever possible. This work would allow better understanding of the limitations and benefits of both polymer types, and would expediate the development of polymers with lower lifetime environmental impact.

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